THE NORTHERN MARSHALL ISLANDS RADIOLOGICAL SURVEY: DATA AND DOSE ASSESSMENTS

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Abstract—**Fallout from atmospheric nuclear tests, especially from those conducted at the Pacific Proving Grounds between 1946 and 1958, contaminated areas of the Northern Marshall Islands. A radiological survey at some Northern Marshall Islands was conducted from September through November 1978 to evaluate the extent of residual radioactive contamination. The atolls included in the Northern Marshall Islands Radiological Survey (NMIRS) were Likiep, Ailuk, Utirik, Wotho, Ujelang, Taka, Rongelap, Rongerik, Bikar, Ailinginae, and Mejit and Jemo Islands. The original test sites, Bikini and Enewetak Atolls, were also visited on the survey. An aerial survey was conducted to determine the external gamma exposure rate. Terrestrial (soil, food crops, animals, and native vegetation), cistern and well water samples, and marine (sediment, seawater, fish and clams) samples were collected to evaluate radionuclide concentrations in the atoll environment. Samples were processed and analyzed for ^{137}Cs, ^{90}Sr, $^{239+240}$Pu and ^{241}Am. The dose from the ingestion pathway was calculated using the radionuclide concentration data and a diet model for local food, marine, and water consumption. The ingestion pathway contributes 70% to 90% of the estimated dose. Approximately 95% of the dose is from ^{137}Cs. ^{90}Sr is the second most significant radionuclide via ingestion. External gamma exposure from ^{137}Cs accounts for about 10% to 30% of the dose. $^{239+240}$Pu and ^{241}Am are the major contributors to dose via the inhalation pathway; however, inhalation accounts for only about 1% of the total estimated dose, based on surface soil levels and resuspension studies. All doses are computed for concentrations decay corrected to 1996. The maximum annual effective dose from manmade radionuclides at these atolls ranges from .02 mSv y^{-1} to 2.1 mSv y^{-1}. The background dose in the Marshall Islands is estimated to be 2.4 mSv y^{-1}. The combined dose from both background and bomb related radionuclides ranges from slightly over 2.4 mSv y^{-1} to 4.5 mSv y^{-1}. The 50-y integral dose ranges from 0.5 to 65 mSv.**
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INTRODUCTION

A RADIOLOGICAL survey was conducted from September through November of 1978 in the Northern Marshall Islands prior to the dissolution of the U.S. Trust Territory. The purpose of the survey was to assess the concentrations of persistent manmade radionuclides in the terrestrial and marine environments at 11 atolls and 2 islands. The atolls of the Marshall Islands are shown in Fig. 1. The atolls included in the NMIRS were Likiep, Ailuk, Utirik, Wotho, Ujelang, Taka, Rongelap, Rongerik, Bikar, Ailinginae, Bikini, and Mejit and Jemo Islands. A brief stop was also made at Enewetak Atoll. Two of the atolls, Bikini and Enewetak, were the sites of 66 nuclear tests (Simon and Robison 1997).

A reasonable amount of data existed in 1978 for Enewetak Atoll (U.S. AEC 1973). However, little radiological information was available for most islands at Bikini Atoll or for other atolls that were considered most likely to have received fallout from nuclear tests conducted at the Pacific Proving Grounds between 1946 and 1958. The BRAVO test on 1 March 1954 produced the largest yield (15 MT) of the entire test series in the Pacific. The fallout from BRAVO was the primary contaminating event of Bikini and Eneu Islands at Bikini Atoll and the atolls to the east of Bikini. The general fallout pattern of the BRAVO test is shown in Fig. 1.

The NMIRS was essentially designed as a screening survey, which would be used to determine whether or not further detailed sampling effort might be required at any of the atolls. The survey included an aerial radiological reconnaissance to map the external gamma-ray exposure rates over the islands of each atoll. The logistical support for the entire survey was designed to accommodate this operation.

Shore parties collected appropriate terrestrial and marine samples to assess the radiological dose from pertinent food chains to individuals residing on some of the atolls, future residents of uninhabited atolls, or for those who visit and collect food from these atolls. Soils, vegetation, indigenous animals, cistern water, and groundwater were collected from the islands. Reef and pelagic fish, clams, lagoon water, and sediments were obtained from the lagoons.

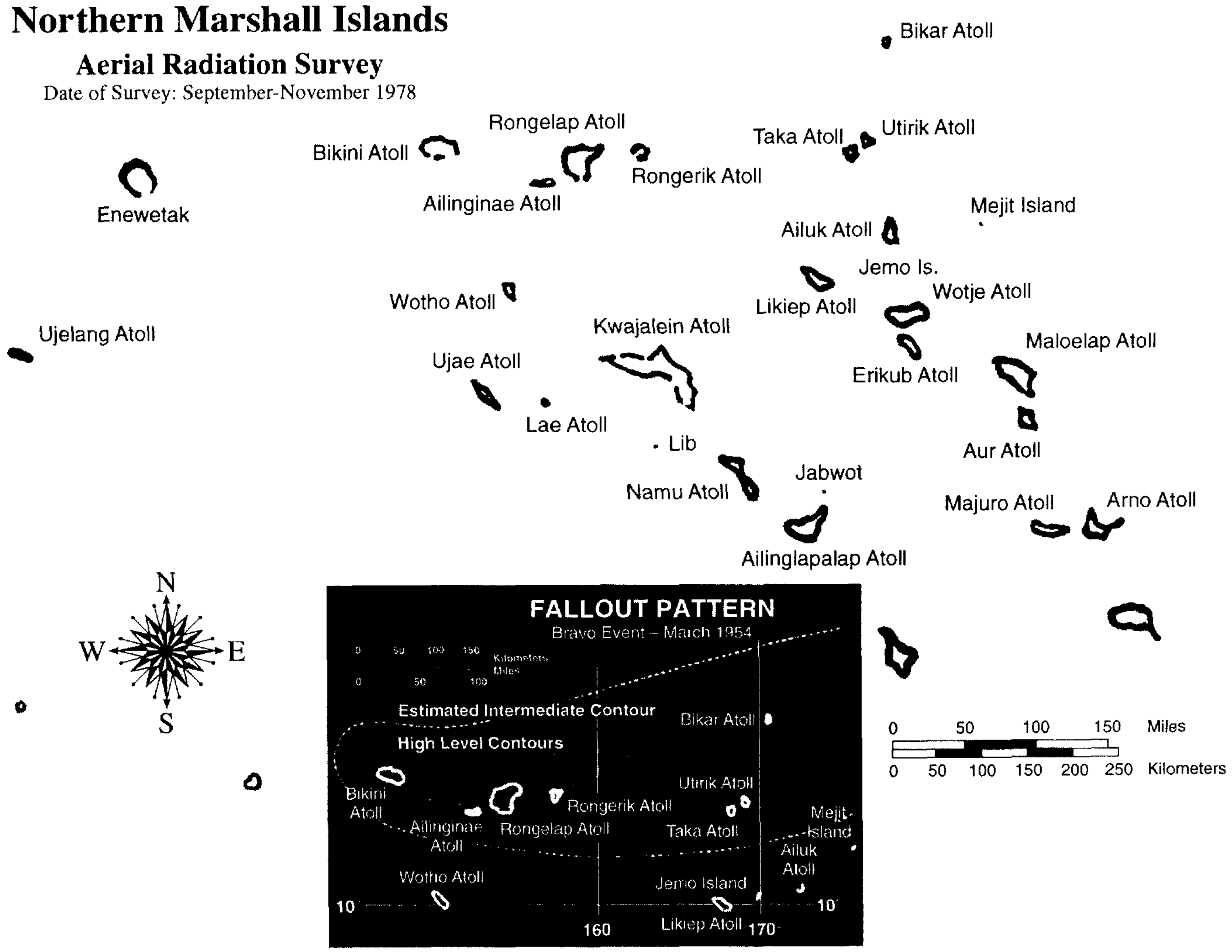

Fig. 1. Atolls and islands of the Northern Marshall Islands radiological survey.

The Lawrence Livermore National Laboratory (LLNL) was responsible for the technical direction of the survey, subsequent sample processing, analytical work, and publishing of results. The Nevada Operations Office (NVOO) of the U.S. Department of Energy (DOE) was responsible for program management in the planning phases and the interaction with other United States agencies and departments and the government and people of the Marshall Islands.

The survey was conducted in three separate segments over a 3-mo period. The first segment of the survey included Rongelap, Taka, Utirik, Bikar, Rongerik, and Ailinginae Atolls. The second segment included Likiep, Ailuk, and Wotho Atolls, and Jemo and Mejit Islands. The concluding third segment included Ujelang and Bikini Atolls, with a limited stop at Enewetak Atoll.

The external gamma aerial survey was conducted from the ship, U.S.N.S. Wheeling, by Edgerton Germeshausen and Grier (EG&G) with the support of a Navy helicopter group, HC-1 Detachment 3, from the North Island Naval Air Station, San Diego, California. The EG&G NaI detector and data analysis system was mounted on one of the two Navy helicopters (Sikorski H-3) carried by the Wheeling and flown by Navy pilots on 46-m grid lines at an altitude of 57 m over the islands at each atoll. A complete report of the external gamma measurement program is available as part of the Northern Marshall Islands survey assessment (Tipton and Meibaum 1981).

The terrestrial and marine programs were conducted primarily with small boats using the Wheeling as an operation base. These two sampling programs were designed as screening surveys to collect adequate samples to make dose estimates for ingestion and inhalation pathways. A second helicopter aboard ship was used to help distribute equipment and marine and terrestrial sampling crews around the atolls. During the first leg of the survey, weather was good and the helicopters were used only for the aerial survey. During the second leg of the survey, only one helicopter was in operation and it was dedicated to the aerial survey. During the third leg, the second helicopter became available and was essential to the terrestrial and marine programs because of adverse weather conditions.

A summary of the numbers and types of samples collected at each atoll is listed in Table 1. Over 5,400 soil, animal, vegetation, fish, clam, sediment, cistern water, and groundwater samples were collected from the 12 atolls and 2 islands during the Northern Marshall Islands survey field operations. All samples were returned to LLNL for processing. The analytical work was conducted both at LLNL and at contract laboratories.

A series of reports were produced that addressed the radionuclide concentrations in cistern water and groundwater, and the estimated doses via ingested water (Noshkin et al. 1981a); the radionuclide concentration in marine species and the associated estimated doses from the marine pathway (Robison et al. 1981b; Noshkin et al. 1981b); the radionuclide concentration in soils, plants, and animals at each of the atolls and islands and the estimated doses via the terrestrial food chain and all other pathways (Robison et al. 1982a); the analytical methods and quality control programs (Jennings and Mount 1983); the data base; and the sampling, processing, and analytical methods and summary (Robison et al. 1981a). A separate report was written for Bikini Atoll (Robison et al. 1982b).

Since the 1978 NMIRS, extensive data bases have been developed for Rongelap, Enewetak, and Bikini Atolls, and separate, more detailed data and dose assessments have been published (Robison et al. 1987, 1988, 1994, 1997; Robison and Conrado 1996a, b).

This report summarizes the radiological concentrations and doses from all pathways developed for the NMIRS. All data are decay corrected to 1996 to represent current conditions. Detailed results are summarized in the original reports.

SAMPLE COLLECTION PROCEDURES

Terrestrial samples (plant, animal, soil, and water)

The field collections were designed to take a representative sample of the locally grown food supplies available to the local populations and to determine the radionuclide concentrations in animals and plants relative to soils for an entire island and atoll. At inhabited atolls, local residents were hired to assist field crews in the collection of the samples.

Representative samples of available local food supplies consisted of animals, fowl, and food grown on the islands. Coconuts are the most common and abundant of the food plants and provided a common type of sample at all atolls. When found by field teams, *Pandanus*, breadfruit, papaya, banana, squash, and *Tacca* (arrowroot) were also collected. If no food crops were available on an island, then native plants such as *Morinda* fruit, and *Scaevola*, *Pisonia*, and *Messerschmedia* leaves were collected so estimates of the radionuclide concentration in food crops could be developed using correlation coefficients (activity per gram in one plant species divided by the activity per gram in a different species).

Pigs and chickens, which represent the major source of meat protein outside of imported canned meats, were collected for analysis of various organs. Coconut crabs were collected when found.

Soil profile samples were collected in the root zone of most of the sampled plants. The radionuclide concentrations measured in the plant tissue could then be compared to concentrations in the soil. Approximately 1 kg sample of soil was taken in the following increments: 0–5, 5–10, 10–15, 15–25, 25–40, and 40–60 cm. A 40-cm-deep profile encompasses most of the active root zone of the subsistence crops that grow in the Northern Marshall Islands. A trench was dug radially from the trees to minimize root damage using either a backhoe or

Table 1. Total number of samples collected and analyzed by atoll or island from the NMIRS.

Atoll	No. of islands	Soil	Vegetation	Animal[a]	Fish[a]	Clams[a]	Cistern water	Ground water	Lagoon water	Lagoon sediment	Total samples
Rongelap[b]	12	398	143	28	149	10	2	2	7	9	748
Taka	3	53	17	0	42	10	0	0	2	4	128
Utirik	5	271	116	22	42	12	1	1	4	6	475
Bikar	3	41	8	0	54	6	0	0	3	4	116
Rongerik	6	161	58	1	84	10	0	0	4	6	324
Ailinginae	10	225	79	2	90	12	1	0	4	10	423
Likiep	10	266	103	24	79	8	3	3	4	9	499
Jemo Island	1	18	6	0	24	0	0	0	0	3	51
Mejit Island	1	48	26	23	6	0	0	0	0	3	106
Ailuk	9	262	102	24	54	6	3	3	4	8	466
Wotho	4	174	48	15	60	7	1	1	4	7	317
Ujelang	7	279	114	14	42	8	1	1	5	5	469
Bikini[b]	15	891	127	0	179	12	2	4	7	11	1,233
Enewetak[b]	5	6	14	0	60	0	0	0	0	0	80
Total	91	3,093	961	153	965	101	14	15	48	85	5,435

[a] Values for animals, fish, and clams are the number of tissues prepared for analysis.
[b] Additional radiological data have been developed over the years (Robison et al. 1987, 1988, 1994, 1997; Robison and Conrado 1996a,b).

shovel. Additional soil profiles were collected at sites around the islands with no associated plant samples.

Groundwater (well water) and cistern water (rainwater collected from dwelling roofs) samples were collected whenever available at the atolls. The groundwater was filtered through 1- and 0.4-μm filters to separate particulates. Cistern water was not filtered.

Marine samples (seawater, sediment, fish, and clams)

Large-volume seawater samples were taken from various locations in each lagoon. All samples were filtered through a 1-μm cylindrical fiber-cartridge filter into plastic barrels to separate particulates. Sediment samples were also collected at these locations. Additional sediment samples were collected from other locations around the inner perimeter of the lagoons.

Throw nets were used exclusively to catch reef fish at the atolls. Large pelagic and benthic fish were collected on sport fishing gear.

Specific species collected represented those commonly eaten by the Marshallese and found in relative abundance at different locations. In addition, we collected species with a variety of feeding habits, and for those which previous radiological data were available.

SAMPLE PROCESSING PROCEDURES

Terrestrial samples

Most vegetation samples were a composite on the average of five individual fruits. The plant samples were washed to remove any soil, dissected into different segments (i.e., meat, skin, and seeds) and weighed. The samples were then freeze-dried, reweighed, and ground to a homogeneous texture. Juices were slowly evaporated in ovens to approximately 200 ml (Robison et al. 1981a). The animal samples were dissected into different organs and tissues, weighed, dried and ground. The soil samples were dried and ball milled to produce a homogenous sample.

The ground vegetation, animal, and soil samples were pressed into an aluminum can or vial, with volumes of 222 cm^3 and 42 cm^3 respectively, and sent for analysis by gamma spectrometry of ^{137}Cs and other gamma emitting radionuclides. Detailed processing procedures are outlined in Stuart (1995).

When gamma analysis was complete, the canned samples were sent to a contract laboratory for wet chemistry analysis for ^{90}Sr, $^{239+240}Pu$, and ^{241}Am. Duplicates and standards, blind to the analyst, were included with each group of samples sent for analysis. A complete report on the quality control program is a part of the original series of reports (Jennings and Mount 1983). The quality control program was conducted independently by C. D. Jennings of Western Oregon State College, Oregon.

Marine samples

Filtered water samples were transferred to large, plastic processing containers where they were acidified, and standardized carrier solutions were added. The radionuclides were separated from the water using published procedures (Wong et al. 1994). The filters (particulate fractions) were dry ashed, gamma counted, dissolved, and specific radionuclides separated by standard procedures.

Frozen sediment samples were thawed, weighed wet, and dried in ovens to a constant weight. The sediment was then homogenized using a shaker-type ball mill and placed in the aluminum cans or vials for analysis by gamma spectrometry.

Fish and vertebrate samples from each location were thawed, weighed, measured, and dissected into distinct tissues and organs. Sample tissues from the same catch and species were pooled to produce a large enough sample for analysis. The samples were oven dried, dry ashed, homogenized, and put in aluminum cans or vials for gamma analysis.

Wet chemistry analyses at LLNL were performed by standard methodology (Wong et al. 1994). Each contractor laboratory used their own procedures, but had to meet our quality control criteria (Jennings and Mount 1983).

DOSE CALCULATION METHODOLOGY

The analytical results from the analysis of these samples along with the EG&G external gamma data were the basis for the dose assessments at the atolls and islands.

The dose estimates for each island were calculated for 1996 assuming residence on the island and the consumption of local foods grown on the island. We used Spiers methods (Spiers 1968) in conjunction with models developed by Bennett (1973, 1977), Bennett and Klusek (1978), and Bennett and Harley[¶] to calculate the bone marrow dose from ^{90}Sr. For other radionuclides, the dose calculations were made using dose models described in the Bikini Island dose assessment report in this issue (Robison et al. 1997). The gut transfer factors used for $^{239+240}Pu$ and ^{241}Am in the 1978 dose calculations were 10^{-4} and 5×10^{-4}, respectively. The biological half-lives used for plutonium and americium were 100 y for bone and 40 y for liver. Plutonium and americium were assumed to be class-W compounds for the inhalation dose calculations.

The radionuclide concentration data used for the ingestion pathway dose estimates are listed in detail for terrestrial foods, marine foods, and water in the original reports (Robison et al. 1981b, 1982a; Noshkin et al. 1981a). A summary for the most important food is given in Tables 2, 3, and 4 for representative islands at each atoll, decay corrected to 1996.

The ingestion doses in this report are based on a diet model that includes both locally grown and imported foods. This diet model, and its relevance to dose estimates in the Marshall Island, is discussed in two reports

¶ Personal communication, Bennett, B. C.; Harley, J. United States Department of Energy Environmental Measurements Laboratory, New York, NY; 1979.

Table 2. The mean concentrations of radionuclides for the major terrestrial foods collected on representative islands at each atoll.

	Radionuclide concentrations in Bq kg^{-1} wet weight[a]																			
	Drinking coconut meat					Copra meat					Pandanus[b]					Breadfruit				
Atoll/Island	N[c]	^{137}Cs	^{90}Sr	$^{239+240}$Pu	^{241}Am[d]	N[c]	^{137}Cs	^{90}Sr	$^{239+240}$Pu	^{241}Am[d]	N[c]	^{137}Cs	^{90}Sr	$^{239+240}$Pu	^{241}Am[d]	N[c]	^{137}Cs	^{90}Sr	$^{239+240}$Pu	^{241}Am[d]
Rongelap *(Northern)*																				
Naen	2	151	—	—	—	2	244	5.8	—	—	1	352	13	1.5×10^{-3}	5.0×10^{-3}	—	—	—	—	—
Kabelle	1	66	—	—	—	2	334	3.1	4.0×10^{-3}	7.4×10^{-3}	—	—	—	—	—	—	—	—	—	—
Rongelap *(Southern)*																				
Rongelap	3	64	—	—	—	18	149	0.55	2.1×10^{-3}	2.9×10^{-3}	9	275	16	1.8×10^{-3}	9.6×10^{-4}	2	65	1.9	9.8×10^{-3}	8.2×10^{-3}
Arbar	1	17	—	—	—	—	—	—	—	—	2	42	28	5.8×10^{-4}	$<8.2 \times 10^{-4}$	—	—	—	—	—
Rongerik																				
Rongerik	2	61	—	—	—	2	55	0.30	$<6.1 \times 10^{-4}$	1.1×10^{-3}	2	60	1.1	$<3.9 \times 10^{-5}$	8.5×10^{-3}	—	—	—	—	—
Enewetak	4	59	0.69	$<8.4 \times 10^{-4}$	$<8.7 \times 10^{-4}$	6	88	0.49	2.0×10^{-3}	3.0×10^{-3}	1	97	1.4	2.7×10^{-3}	2.9×10^{-3}	—	—	—	—	—
Ailinginae																				
Sifo	1	10	—	—	—	3	20	0.61	7.5×10^{-4}	$<4.3 \times 10^{-4}$	1	33	—	—	—	—	—	—	—	—
Utirik																				
Utirik	7	24	—	—	—	11	45	0.073	4.8×10^{-3}	—	9	43	2.3	2.1×10^{-3}	5.2×10^{-3}	2	16	0.44	5.5×10^{-4}	8.9×10^{-4}
Taka																				
Taka	2	3.5	—	—	—	3	10	0.096	$<4.5 \times 10^{-5}$	$<6.7 \times 10^{-4}$	3	3.5	0.59	$<9.8 \times 10^{-5}$	$<2.8 \times 10^{-4}$	—	—	—	—	—
Likiep																				
Likiep	1	6.8	0.072	$<6.1 \times 10^{-4}$	$<1.3 \times 10^{-3}$	4	15	0.056	-3.9×10^{-4}	9.5×10^{-4}	3	9.3	0.93	1.4×10^{-4}	6.8×10^{-4}	2	13	0.10	1.7×10^{-4}	3.9×10^{-4}
Mejit Island	4	19	0.026	-6.8×10^{-4}	-3.0×10^{-4}	1	34	0.027	$<2.3 \times 10^{-4}$	9.7×10^{-4}	3	30	0.26	3.1×10^{-4}	$<8.3 \times 10^{-4}$	3	23	0.023	1.6×10^{-4}	3.6×10^{-4}
Ailuk																				
Ailuk	5	15	0.014	-7.0×10^{-5}	$<2.9 \times 10^{-4}$	2	27	0.037	1.6×10^{-3}	$<4.2 \times 10^{-4}$	2	54	0.53	2.3×10^{-4}	$<3.3 \times 10^{-4}$	3	6.8	0.29	2.2×10^{-4}	4.2×10^{-4}
Wotho																				
Wotho	7	6.2	—	—	—	—	—	—	—	—	3	5.2	0.40	5.2×10^{-4}	7.7×10^{-4}	2	2.1	0.071	2.0×10^{-4}	2.6×10^{-4}
Ujelang																				
Ujelang	7	5.2	0.13	$<1.5 \times 10^{-4}$	$<8.7 \times 10^{-4}$	7	15	0.073	1.1×10^{-3}	1.4×10^{-3}	6	5.2	0.52	4.9×10^{-4}	$<2.3 \times 10^{-4}$	3	14	0.13	4.8×10^{-4}	$<3.7 \times 10^{-4}$
Bikar																				
Bikar	—	—	—	—	—	1	19	—	—	—	—	—	—	—	—	—	—	—	—	—
Jemo Island	2	7.9	—	—	—	1	4.5	—	—	—	—	—	—	—	—	—	—	—	—	—

[a] Specific activity decay corrected to 1996.
[b] Fruit was separated into meat and juice. Specific activity may represent either meat and juice together or individually if either fraction was unavailable.
[c] Number of samples collected. For ^{90}Sr, $^{239+240}$Pu and ^{241}Am, not all samples were analyzed. Each sample consists of approximately five fruits.
[d] Specific activity for ^{241}Am reflects the in growth from ^{241}Pu decay since 1978.

Table 3. The mean concentrations of radionuclides in muscle tissue from animals collected on representative islands at each atoll.

	Radionuclide concentrations in Bq kg^{-1} wet weight[a]														
	Pork					Chicken					Coconut Crab				
Atoll/Island	N[b]	^{137}Cs	^{90}Sr	$^{239+240}Pu$	^{241}Am[c]	N[b]	^{137}Cs	^{90}Sr	$^{239+240}Pu$	^{241}Am[c]	N[b]	^{137}Cs	^{90}Sr	$^{239+240}Pu$	^{241}Am[c]
Rongelap															
Rongelap	2	212	0.087	1.4×10^{-3}	2.8×10^{-3}	1	64	0.13	2.5×10^{-3}	4.1×10^{-3}	—	—	—	—	—
Arbar	—	—	—	—	—	—	—	—	—	—	2	87	38	0.072	0.028
Ailinginae															
Sifo	—	—	—	—	—	—	—	—	—	—	1	41	2.2	0.025	4.3×10^{-3}
Utirik															
Utirik	2	83	0.036	$<4.0 \times 10^{-4}$	$<7.7 \times 10^{-4}$	1	14	0.19	9.5×10^{-4}	2.3×10^{-3}	—	—	—	—	—
Likiep															
Likiep	2	44	—	—	—	2	2.7	—	—	—	—	—	—	—	—
Mejit Island	2	44	9.7×10^{-3}	1.6×10^{-4}	1.8×10^{-3}	2	12	0.014	1.0×10^{-3}	1.2×10^{-3}	—	—	—	—	—
Ailuk															
Ailuk	2	32	0.094	$<1.7 \times 10^{-4}$	7.7×10^{-4}	1	8.8	0.027	$<3.6 \times 10^{-4}$	1.8×10^{-3}	—	—	—	—	—
Wotho															
Wotho	1	16	1.9×10^{-3}	$<1.4 \times 10^{-4}$	$<1.1 \times 10^{-4}$	1	2.6	4.6×10^{-3}	1.0×10^{-3}	—	—	—	—	—	—
Ujelang															
Ujelang	2	11	0.014	6.6×10^{-4}	5.0×10^{-4}	—	—	—	—	—	—	—	—	—	—

[a] Specific activity decay corrected to 1996.
[b] Number of samples collected.
[c] Specific activity for ^{241}Am reflects the in growth from ^{241}Pu decay since 1978.

Table 4. The mean concentrations of radionuclides in muscle tissue from fish and clams collected at each atoll or island. NOTE: Non-detected concentrations are equal to the maximum detection limit and are noted by the < symbol.

	Radionuclide concentrations in mBq kg^{-1} wet weight[a]														
	Reef fish					Pelagic fish					Clams				
Atoll	N[b]	^{137}Cs	^{90}Sr	$^{239+240}Pu$	^{241}Am[c]	N[b]	^{137}Cs	^{90}Sr	$^{239+240}Pu$	^{241}Am[c]	N[b]	^{137}Cs	^{90}Sr	$^{239+240}Pu$	^{241}Am[c]
Rongelap	598	586	17	11	1.4	7	684	<7.3	0.22	0.27	3	48	160	81	46
Rongerik	283	317	12	2.6	0.41	7	611	<7.3	0.52	<0.27	3	146	109	13	14
Ailinginae	279	342	12	3.7	0.91	4	537	<7.3	0.37	<0.37	4	<14	24	13	9.1
Utirik	110	298	<21	8.5	0.46	3	469	<9.8	<0.37	<0.46	19	25	<61	16	<2.7
Taka	129	220	12	4.4	0.91	3	684	<4.9	0.19	<0.14	3	<41	<81	15	<9.0
Likiep	294	269	17	1.5	0.91	—	—	—	—	—	4	<20	<34	12	<2.5
Mejit Island	70	171	—	<0.07	—	—	—	—	—	—	—	—	—	—	—
Ailuk	172	220	<12	1.5	<0.46	1	391	<17	0.74	0.23	3	<25	<29	3.7	<1.4
Wotho	298	317	<7.0	1.5	0.46	2	488	4.9	<0.15	0.14	2	<12	<83	3.3	4.6
Ujelang	77	147	5	<0.11	<0.23	87	488	<7.3	0.74	<0.46	13	30	<98	22	16
Bikar	140	415	12	1.5	0.46	4	635	9.8	0.37	<0.46	3	65	<49	4.8	32
Jemo Island	99	391	<24	1.5	<3.7	—	—	—	—	—	—	—	—	—	—

[a] Specific activity decay corrected to 1996.
[b] Number of individual fish or clams collected. Samples were pooled from the same catch and species, and this number does not represent the number of analyses performed.
[c] Specific activity for ^{241}Am reflects the in growth from ^{241}Pu decay since 1978.

in this issue (Robison et al. 1997; Robison and Sun 1996).

The external gamma measurements made with the aerial system by EG&G were the main data used at most atolls to determine the external gamma dose at the islands. Detailed data showing specific contours for each island are available in the original report (Tipton and Meibaum 1981). The resolution on island surface for the aerial measurements was about 100 m. Additional external gamma data were available for Bikini and Eneu Islands at Bikini Atoll. A major external gamma survey was conducted at these 2 islands by LLNL in 1975 (Gudiksen et al. 1976). The survey was conducted on the ground using portable gamma-rate meters at 1 m height. The survey on Bikini Island was conducted at 30-m intervals over the whole island resulting in about 2,100 measurements. The external gamma measurements at Eneu were made at 100-m intervals. The EG&G contours for Bikini Island developed from the aerial measurement were very consistent with the contours developed from the ground survey with a 30-m resolution. The surveys also agreed very well at Eneu Island.

The dose estimates for external gamma exposure were made using the island average exposure rate for ^{137}Cs and ^{60}Co. No shielding was included. Dose estimates subsequent to the 1978 publications use established time distributions for various areas of the islands and measurements made inside houses and around the

Table 5. The mean concentrations of radionuclides in soil collected on representative islands at each atoll. NOTE: Non-detected concentrations are equal to the maximum detection limit and are noted by the < symbol.

		Radionuclide concentrations in Bq kg^{-1} dry weight[a]																			
		^{137}Cs					^{90}Sr					$^{239+240}Pu$					^{241}Am[c]				
		Soil increment, cm					Soil increment, cm.					Soil increment, cm					Soil increment, cm				
Atoll/Island	N[b]	0–5	5–10	10–15	15–25	25–40	0–5	5–10	10–15	15–25	25–40	0–5	5–10	10–15	15–25	25–40	0–5	5–10	10–15	15–25	25–40
Rongelap (Northern)																					
Naen	7	2,374	1,615	1,078	249	83	3,741	2,793	804	344	131	1,070	770	407	83	25	569	435	207	48	17
Kabelle	5	930	318	196	243	82	1,133	422	556	422	136	526	116	131	106	26	309	23	11	23	21
Rongelap (Southern)																					
Rongelap	27	368	256	147	68	34	168	193	144	109	62	117	79	34	10	4.7	46	36	18	7.6	3.6
Arbar	6	303	340	167	58	16	—	—	—	—	—	—	—	—	—	—	173	—	—	—	—
Rongerik																					
Rongerik	7	829	305	134	49	19	740	259	274	114	53	87	20	26	6.1	1.3	223	36	15	3.8	0.73
Enewetak	11	162	97	52	29	20	142	176	43	45	—	92	52	11	2.5	—	54	60	—	2.0	—
Ailinginae																					
Sifo	6	36	32	24	5.6	2.9	36	52	—	—	—	15	12	—	—	—	8.4	8.6	8.0	2.3	—
Utirik																					
Utirik	28	60	28	16	7.4	4.1	34	26	20	8.9	5.8	17	8.8	3.1	0.88	0.57	11	5.5	2.3	0.43	0.80
Taka																					
Taka	8	28	24	10	6.6	2.7	29	20	13	4.2	4.2	4.5	1.3	1.7	0.28	0.18	5.7	3.1	0.92	0.22	0.11
Likiep																					
Likiep	12	17	7.0	4.1	2.5	1.3	6.3	4.3	3.3	2.2	1.0	2.0	1.2	0.45	0.23	0.054	1.5	0.90	0.33	0.15	0.038
Mejit Island	8	12	6.5	4.6	2.1	1.1	7.5	6.3	6.1	5.0	2.1	2.2	1.0	0.70	0.38	0.092	1.6	0.77	0.54	0.20	0.070
Ailuk																					
Ailuk	13	15	7.6	4.6	2.9	1.5	6.3	8.5	6.2	4.0	2.3	3.6	2.4	0.54	0.20	0.066	2.7	0.58	0.47	0.20	0.053
Wotho																					
Wotho	15	10	5.4	4.1	1.5	0.82	3.0	2.7	2.7	1.2	0.66	1.1	0.51	0.18	0.043	0.013	1.0	0.26	2.0	3.1	2.2
Ujelang																					
Ujelang	24	13	8.8	6.6	3.3	1.9	4.9	4.2	3.0	2.5	1.4	1.5	0.96	0.70	0.23	0.089	0.59	0.52	0.20	0.32	0.046
Bikar																					
Bikar	2	11	11	11	12	3.3	21	20	—	—	—	1.7	2.3	—	—	—	4.3	1.8	3.3	4.7	<1.5
Jemo Island	3	8.2	7.4	7.1	1.3	<0.13	5.9	7.4	—	—	—	1.4	1.1	—	—	—	0.49	0.34	<0.87	<0.76	<0.90

[a] Specific activity decay corrected to 1996.
[b] Number of profiles collected and analyzed. For ^{90}Sr, $^{239+240}Pu$ and ^{241}Am, a small percentage did not meet the quality control criteria established and are not included in the reported concentrations.
[c] Specific activity for ^{241}Am reflects the in growth from ^{241}Pu decay since 1978.

village center and living areas. These are combined to develop more realistic external dose estimates as described in the Bikini dose assessment in this issue (Robison et al. 1997).

$^{239+240}$Pu and ^{241}Am are the major contributors to radiological dose via the inhalation pathway. The methodology is based on resuspension experiments conducted at 3 different atolls in the Marshall Islands. The dose estimates from the inhalation pathway are based on a mass loading model developed from our Bikini Island resuspension studies and discussed in other reports in this issue (Robison et al. 1997; Shinn et al. 1997). The surface soil (0–5 cm) is the source of $^{239+240}$Pu and ^{241}Am particulates resuspended in the air by wind action and available for inhalation. The dose estimates via inhalation at the various islands were determined by using the $^{239+240}$Pu and ^{241}Am concentration in the surface soils at each island, the mass loading model, and a breathing rate of 22 m^3 d^{-1} to determine the daily inhalation of plutonium and americium. The ICRP lung model used to estimate the dose was the lung model given in ICRP 30 (1982).

RESULTS

The radionuclide concentrations were determined for most of the food items listed in the diet model used for dose assessment. If food samples were available for an island, then the data were used. For those atolls where some food crops and animals were unavailable, the radionuclide concentration was estimated by applying concentration ratios (activity per gram in vegetation divided by the activity per gram in soil) or correlation coefficients that were developed at atolls where such food crops were available, to the soil or plants at those islands where direct data were unavailable. Data for fish and clams, for islands where some species were not caught, were extrapolated for lagoons where similar conditions existed. A total of 26,018 analyses, by both gamma spectroscopy and wet chemistry, resulted from the NMIRS (Robison et al. 1981a).

The mean radionuclide concentrations of ^{137}Cs, ^{90}Sr, $^{239+240}$Pu, and ^{241}Am for the major local terrestrial foods found in the Marshallese diet are given for the residence islands or major land masses of each atoll in Tables 2 and 3. These data are representative of each atoll sampled. Data for the other islands at the atolls and minor food items collected can be found in the original reports (Robison et al. 1982a).

Coconut consumption is the major source of radionuclide intake from local foods. Two distinct growth stages exist in the diet model for coconut-drinking and copra. Drinking coconuts have a dry to wet weight ratio of less than 0.45. Copra coconuts have a ratio greater than or equal to 0.45. ^{137}Cs concentrations are much lower in the drinking than the copra coconuts. Calculated doses are dependent on differentiating between the stages of coconut.

The mean radionuclide concentrations for the marine species found in the diet model by atoll or island are found in Table 4. A more detailed breakdown by species and tissue can be found in the original reports (Robison et al. 1981b; Noshkin et al. 1981b). Sediment and sea water can be used for further comparison of radionuclide conditions found in the marine environment. These results can be found in Noshkin et al. (1987a, b).

Cistern and ground water are also found in the diet model. The drinking water pathway contributes a small portion of radionuclides to the total estimated doses. Radionuclide concentrations and dose assessments of cistern and ground water are found in the original reports (Noshkin et al. 1981a).

Soil radiological conditions at the representative islands at each atoll are characterized in Table 5. The mean concentrations of ^{137}Cs, ^{90}Sr, $^{239+240}$Pu and ^{241}Am are listed by increments in the soil profile. The decrease in activity with depth is exponential as shown in Fig. 2. Approximately 80% of the activity is in the top 15 cm of the soil column for atolls and islands sampled.

The external gamma data generated by EG&G used for the dose assessment are listed in Table 6. The mean value was used for calculating the external gamma dose at each island. The range of exposure rate contours that encompass most of the land area for each island are also listed.

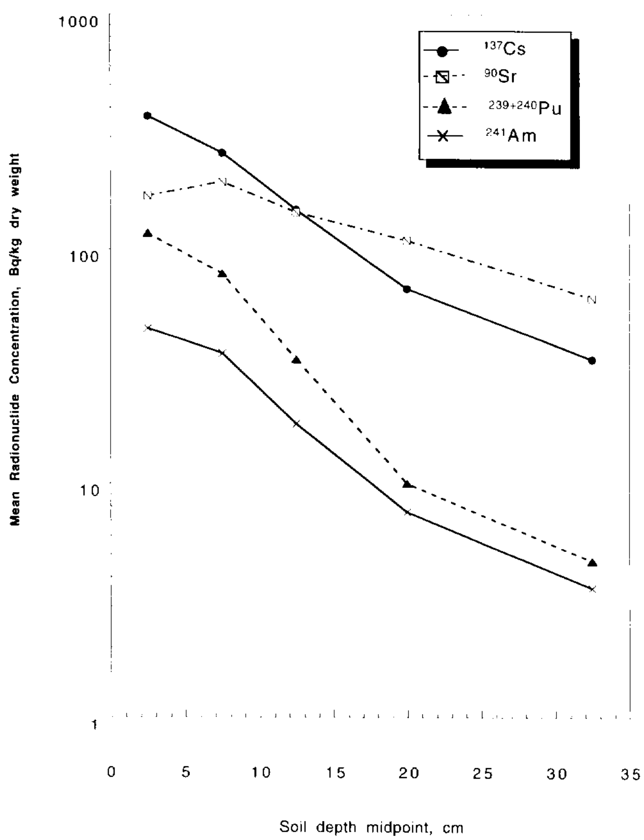

Fig. 2. Mean radionuclide concentrations in soil at Rongelap Island, Rongelap Atoll. The exponential reduction in concentration as a function of soil depth, is representative of soil profiles at other islands and atolls summarized in this report.

Table 6. External gamma exposure rates at atolls and islands included in the NMIRS.[a]

Atoll/Island	Mean $\mu R\ h^{-1}$	Major contours $\mu R\ h^{-1}$	Atoll/Island	Mean $\mu R\ h^{-1}$	Major contours $\mu R\ h^{-1}$
Bikini			*Utirik*		
Nam	14	9–40	Aon	0.46	0.43–0.92
Iroij	4.5	0.5–5.9	Bigrak	0.50	0.43–0.92
Odrik	1.1	0.23–0.92	Utirik	0.48	0.43–0.92
Lomilik	14	1.5–13	*Taka*		
Aomen	3.0	0.23–1.5	Taka	0.28	0.20–0.43
Bikini	20	20–40	*Likiep*		
Rojkere	9.9	4.0–9.2	Jiebaru	0.13	0.09–0.20
Eneu	1.5	0.9–4.0	Kapenor	0.15	0.09–0.20
Aerokojilol	0.33	0.08–0.23	Mato	0.14	0.09–0.20
Lele, Eneman	0.86	0.08–0.92	Likiep	0.13	0.09–0.20
Enidrik	2.8	1.5–9.2		0.18	0.09–0.20
Lukoj	24	9–26	*Mejit Island*		
Jelete	29	20–40	*Ailuk*		
Oroken	7.3	2.6–5.9	Enejelar	0.17	0.09–0.20
Rongelap			Bigen	0.16	0.09–0.20
Borukka	4.5	2.6–4.0	Agulue	0.14	0.09–0.20
Kabelle	9.2	4.0–13	Aliet	0.15	0.09–0.20
Eniaetok	6.6	4.0–9.2	Ailuk	0.13	0.09–0.20
Lomilal	21	13–26	Berejao	0.13	0.09–0.20
Yugui	25	13–26	Kapen	0.17	0.09–0.20
Rongelap	3.0	1.5–4.0	*Wotho*		
Arbar	2.7	1.5–2.6	Medyeron	0.13	0.09–0.20
Naen	28	20–40	Wotho	0.13	0.09–0.20
Lukuen	18	9–20	Kabben	0.15	0.09–0.20
Gabelle	5.8	4.0–5.9	*Ujelang*		
Gogan	8.6	1.5–5.9	Eimnlapp	0.15	0.09–0.20
Busch	3.6	1.5–4.0	Kalo	0.14	0.09–0.20
Tufa	3.0	0.9–2.6	Daisu	0.14	0.05–0.09
Rongerik			Ujelang	0.13	0.09–0.20
Eniwetak	3.2	1.5–2.6	*Bikar*		
Bigonattam	4.3	4.0–5.9	Jaboerukku	0.33	0.20–0.43
Lotoback	3.8	2.6–4.0	Bikar	0.34	0.20–0.43
Brock	5.0	4.0–5.9	*Jemo Island*	0.15	0.09–0.20
Rongerik	4.0	4.0–5.9			
Ailinginae					
Ucchuwanen	1.3	0.50–0.92			
Knox	0.92	0.50–0.92			
Mogiri	1.3	0.23–0.92			
Sifo	0.92	0.23–0.92			
Ribinouri	1.3	0.50–0.92			
Enibuk	1.1	0.50–0.92			
Majokoryaan	1.7	0.92–1.5			

[a] Data from Tipton and Meibaum 1981, decay corrected to 1996.

The estimated maximum annual doses (defined as that year when the sum of the dose from all radionuclides and pathways is a maximum) based on the diet model and radionuclide concentrations in food, water, and air and the external gamma exposure at the islands are listed in Table 7. The results are for 1996 conditions at the islands and were generated by correcting the original doses for radiological decay from 1978 to 1996 for both ^{137}Cs and ^{90}Sr. The 50-y integral effective doses from all exposure pathways are also listed in Table 7. The 50-y integral dose can be used for providing risk estimates for the population.

An example of the relative importance of radionuclide and pathway contributions to the total estimated dose can be found in Robison et al. (1997). In general, the ingestion pathway at the various atolls contributes 70% to 90% of the estimated dose mostly from ^{137}Cs (~95%). The external gamma exposure from ^{137}Cs accounts for about 10% to 30% of the estimated dose. Other pathways and radionuclides account for about 3% or less of the estimated dose. The concentrations of ^{90}Sr, $^{239+240}$Pu and ^{241}Am are very low in all edible foods and contribute in a minor way to the total dose. Resuspension at the atolls is very low so that the inhalation dose from $^{239+240}$Pu and ^{241}Am is about 1% of the total estimated dose.

DISCUSSION AND CONCLUSION

The close-in fallout pattern from the BRAVO test, shown in Fig. 1, traveled in an easterly direction from Bikini. Atolls east of Bikini and north of a line drawn from the southern half of Enewetak Atoll in the west to above Mejit Island in the east are more contaminated

Table 7. The estimated maximum annual effective doses and the 50-y integral effective doses in 1996 for atolls and islands included in the NMIRS.

Atoll/Island	Annual dose mSv y^{-1}	50-y integral dose, mSv	Atoll/Island	Annual dose mSv y^{-1}	50-y integral dose, mSv	Atoll/Island	Annual dose mSv y^{-1}	50-y integral dose, mSv
Rongelap			*Taka*			*Ailuk cont.*		
Naen	2.1	64	Taka	0.03	1.0	Berejao	0.03	0.9
Kabelle	0.9	26	Eluk	0.02	0.7	Kapen	0.03	1.0
Mellu	0.6	18.5	Eluk	0.02	0.7	*Wotho*		
Eniaetok	0.6	19	*Likiep*			Medyeron	0.02	0.5
Rongelap	0.4	11	Agony	0.02	0.8	Wotho	0.02	0.5
Arbar	0.2	6.6	Kapenor	0.02	0.6	Kabben	0.02	0.5
Rongerik			Likiep	0.03	1.1	*Bikar*		
Enewetak	0.3	8.6	Rikuraru	0.02	0.7	Jaboerukku	0.04	1.3
Rongerik	0.4	12	*Mejit Is.*	0.04	1.2	Bikar	0.04	1.3
Ailinginae								
Uechuwanen	0.1	4.6	*Ailuk*			*Jemo Is.*	0.03	0.9
Knox	0.2	5.1	Enijabro	0.03	0.8			
Mogiri	0.2	4.8	Enejelar	0.03	0.9	*Ujelang*		
Sifo	0.1	2.6	Bigen	0.04	1.3	Ujelang	0.02	0.7
Utirik			Agulue	0.03	0.9			
Aon	0.10	3.2	Aliet	0.03	0.8			
Utirik	0.07	2.2	Ailuk	0.03	1.0			

than those lying to the south of this line. The atolls east of Bikini Atoll and north of the above mentioned line received a deposition density of radionuclides that diminished with distance from Bikini Atoll.

For example, the highest radionuclide concentrations in soil and plants, the highest external gamma exposures, and, consequently, the highest estimated doses east of Bikini are at Rongelap Atoll. There is a significant difference between the southern half and the northern half of Rongelap atoll. The concentration of radionuclides in soil and vegetation is about a factor of five lower in the southern half of the atoll (Robison and Conrado 1996a, b). Contamination levels in the northern half of Rongelap are more similar to Bikini Island because the centerline of the fallout pattern crossed the northern half of Rongelap Atoll. The dose estimates in Table 7 reflect this difference with the dose for Rongelap Island being about 0.4 mSv y^{-1} and that for Naen Island in the north being 2.1 mSv y^{-1}.

Rongerik Atoll, just east of Rongelap, has the next highest deposition density of radionuclides. Rongerik is an uninhabited atoll, but assuming residence on Rongerik leads to estimated doses of about 0.4 mSv y^{-1}.

Ailinginae Atoll, which is owned by the Rongelap people, lies just to the southwest of Rongelap Atoll, and as a result of the location, the deposition density of radionuclides and the resultant estimated doses are less than at Rongelap Island. The estimated doses for residence on Ailinginae are about 0.1 to 0.2 mSv y^{-1}.

The deposition density of radionuclides diminishes significantly for atolls south of Ailinginae Atoll and east of Rongerik Atoll. At Utirik Atoll the ^{137}Cs concentrations in the soil and the external gamma exposure are about a factor of 6 less than at Rongelap Island. The estimate dose for Utirik Island is less than 0.1 mSv y^{-1}.

The atolls south of the above mentioned line, Ujelang, Wotho, Ailuk, Likiep, Jemo Island, and Mejit Island, all have much lower concentrations of radionuclides in the soil and plants and lower external gamma exposures than the atolls discussed above that lie to their north. The effective dose estimates all range between 0.02 and 0.04 mSv y^{-1} with the 50-y integral effective dose ranging from 0.5 to 1.3 mSv.

The methodology for calculating the uncertainty and interindividual variability in dose estimates at Bikini Island can be found in this issue (Bogen et al. 1997). The results in this report for Bikini Island are indicative of the range of uncertainty and interindividual variability in estimates for other islands.

The background radiation dose in the Marshall Islands is about 2.4 mSv y^{-1} (Table 8) of which a significant fraction (1.8 mSv) comes from naturally occurring ^{210}Po ingested via consumption of fresh fish (Noshkin et al. 1994). Consequently, the combined dose from background and bomb related radionuclides is less than 2.8 mSv y^{-1} at Rongelap Island, about 2.5 mSv y^{-1} at Ailinginae Atoll, less than 2.5 mSv y^{-1} at Utirik, and only slightly over the background dose of 2.4 mSv y^{-1} at the other inhabited atolls of Ujelang, Wotho, Ailuk, Likiep, and Mejit Island.

For comparison, the average background dose worldwide is about 2.4 mSv y^{-1} with some regions of the world having background doses above 10 mSv y^{-1}

Table 8. Marshall Islands background dose.

Source	Effective dose rate mSv y^{-1}
Cosmic	0.22
Comogenic	0.01
Terrestrial	0.01
^{40}K	0.18
^{210}Po (diet)[a]	1.8
^{210}Pb (diet)[a]	0.20
Total	2.4

[a] Main source is fresh fish in the local diet (Noshkin et al. 1994).

Table 9. ^{137}Cs concentrations in vegetation and soil in the 5–15° latitude band.

	Bq kg^{-1} wet weight[a]								Bq kg^{-1} dry weight[a]			
Locations	N[b]	Drinking coconut meat	N[b]	Drinking coconut juice	N[b]	Breadfruit	N[b]	*Pandanus*	N[b]	Soil 0–5 cm	N[b]	Soil 0–40 cm
Pohnpei[c]	11	5.2	9	1.7	8	4.5	—	—	17	8.1	17	2.8
Pohnpei[d]	1	3.4	—	—	—	—	—	—	3	8.6	—	—
Majuro Atoll[c]	14	3.5	14	1.9	5	1.3	—	—	13	2.9	—	—
Majuro Atoll[d]	2	7.6	—	—	—	—	—	—	1	1.5	—	—
Kwajalein Atoll[c]	13	4.9	14	3.0	2	6.9	1	14	15	6.9	8	2.4
Kwajalein Atoll[e]	1	8.5	—	—	—	—	—	—	—	—	—	—
Guam[d]	2	2.1	—	—	—	—	—	—	2	11	—	—
Truk[d]	3	1.7	—	—	—	—	—	—	1	4.8	—	—
Palau[d]	2	1.0	—	—	—	—	—	—	3	8.3	—	—

[a] Specific activity decay corrected to 1996.
[b] Number of samples.
[c] Specific activity is from samples collected between 1981 and 1990 by LLNL.
[d] Specific activity from Nelson (1979).
[e] Specific activity from Nelson (1977).

(UNSCEAR 1993). The average background dose in the U.S. is about 3 mSv y^{-1} (NCRP 1987). The estimated combined dose at Rongelap Island of less than 2.8 mSv y^{-1} is slightly above the worldwide average of 2.4 mSv y^{-1}, but below the U.S. average of 3 mSv y^{-1}. All other inhabited atolls have combined doses from background and bomb-related radionuclides essentially the same as the world wide average of 2.4 mSv y^{-1}.

The concentration of ^{137}Cs in soils and vegetation from the southern half of Kwajalein Atoll, Majuro Atoll, Pohnpei, Guam, Truk, and Palau that represent worldwide fallout levels for the 5–15°N latitude band, are listed in Table 9. The concentrations of these same radionuclides at Likiep, Ujelang, Wotho, Ailuk, and Jemo and Mejit Islands are about a factor of 2 to 3 above these worldwide fallout levels.

External gamma measurements were performed by Simon and Graham (1994) for the northern and southern atolls in the Marshall Islands. The gamma measurements at the northern atolls of Likiep, Ailuk, and Jemo and Mejit Islands were found to be slightly higher than the southern Marshall Island atolls. The exposure levels at these latter atolls were indistinguishable from worldwide fallout levels at the 0–10°N latitude band.

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